Report from
Neutrino Factory
Physics Study Group

- Superbeam Report Summary
- Current Superbeam Ideas
- Snowmass Epiphany
- HEPAP Subpanel Report
- What happens next in US Neutrino program?
- How can Canada join the fun?

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Vancouver Island, BC

Fermilab Superbeam Study

How do superbeams compete with neutrino factories in terms of physics?
Reminder: "Physics", concentrating on $\nu_\mu \to \nu_e$, assuming LSND is not due to oscillations...

- θ_{13}
- Sign of Matter Effects
- CP violation

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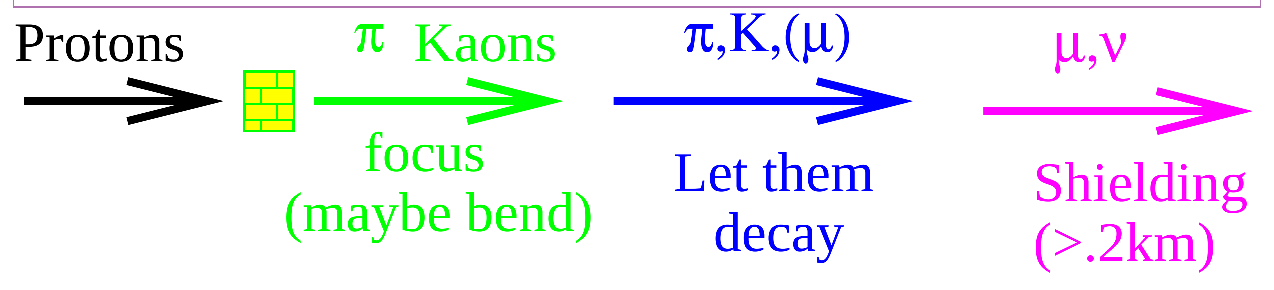
Upgraded Conventional Beams

1. Multi-GeV Neutrino Beams $\surd$
2. 1GeV Neutrino Beams $\surd$
3. Sub-GeV beams (stopped muons)

Making a Conventional Neutrino Beam



For a 2-body decay ($\pi, K \to \mu\nu_\mu$):
Energy of ν at far detector:

$$E_\nu \approx \gamma m_h \frac{m_h^2 - m_\mu^2}{m_h^2}\left(\frac{1}{1+\gamma^2\theta_{\nu h}^2}\right)$$

Flux of Neutrinos per meson at far detector:

$$\Phi \approx BR \frac{1}{4\pi L_{det}^2}\left(\frac{2\gamma}{1+\gamma^2\theta_{\nu h}^2}\right)^2$$

θ = angle between meson and detector
BR = Branching Ratio, γ = Boost of meson

Events per π, μ decay has same γ^3 dependence as muon storage ring! Oops, except for

1. Production Spectra per MW proton power
2. Length of decay pipe (for $\pi \to \nu$)

ν_μ Event Rates in Conventional Beam

For 1.6MW proton power, 732km baseline:
(0.6×10^{20} μ per year or $4\times$ the NUMI POT/year)

Beam	$< E_\nu >$ (GeV)	Events/kt-yr π	μ	E_μ (GeV)
MINOS-LE	3.5	1800	120	4.5
MINOS-ME	7	5760	1120	9.1
MINOS-HE	15	12800	9430	18.2
	20		21770	30

For Conventional Beam, $\nu_\mu \to \nu_e$ signal
For Muon Storage Ring beam, $\nu_e \to \nu_\mu$ signal

Given these event rates for low neutrino energy beams, what's so exciting about storage rings?

It's much easier to look for $\nu_e \to \nu_\mu$ than it is to look for $\nu_\mu \to \nu_e$.

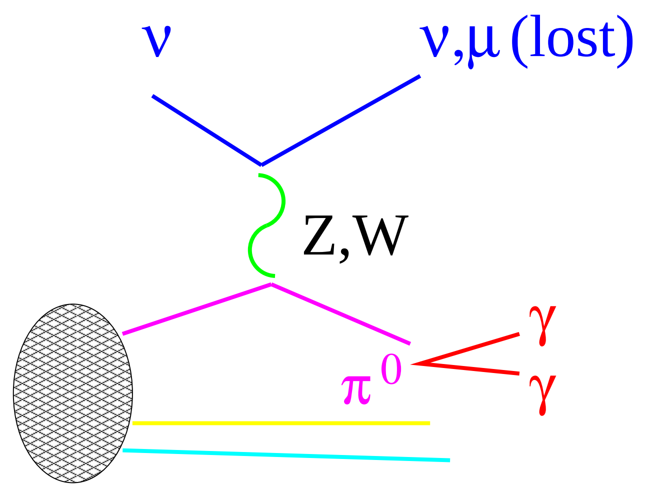
Higher neutrino energies mean higher distances $\to$ Matter effects amplify signal, tell sign of largest mass splitting.

Backgrounds in Conventional Beams

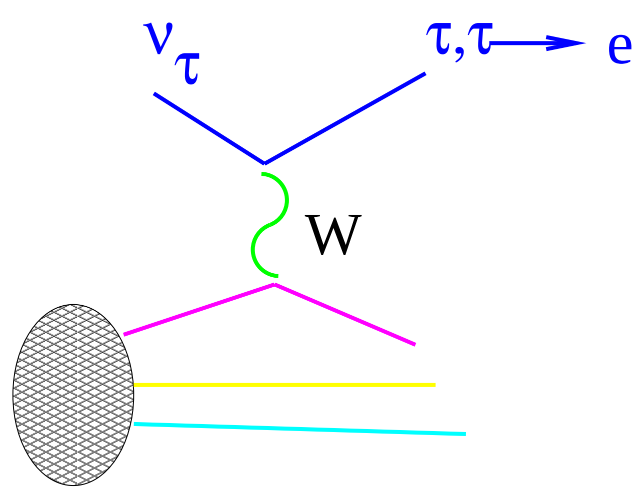
If signal is $\nu_\mu \to \nu_e$ or $\bar{\nu}_\mu \to \bar{\nu}_e$:

Intrinsic ν_e Contamination

$$K^\pm \to \pi^0 e^\pm \nu_e(\bar{\nu}_e)$$
$$\mu^\pm \to e^\pm \bar{\nu}_\mu(\nu_\mu)\nu_e(\bar{\nu}_e)$$
$$K_L \to \pi^\pm e^\mp \nu_e(\bar{\nu}_e)$$
$$\text{Charm} \to X e^\pm \nu_e(\bar{\nu}_e)$$

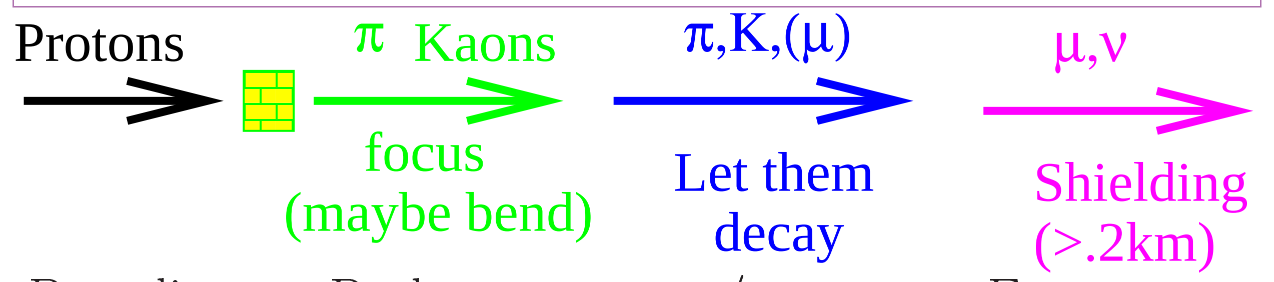


π^0 production in NC and CC (high y) events

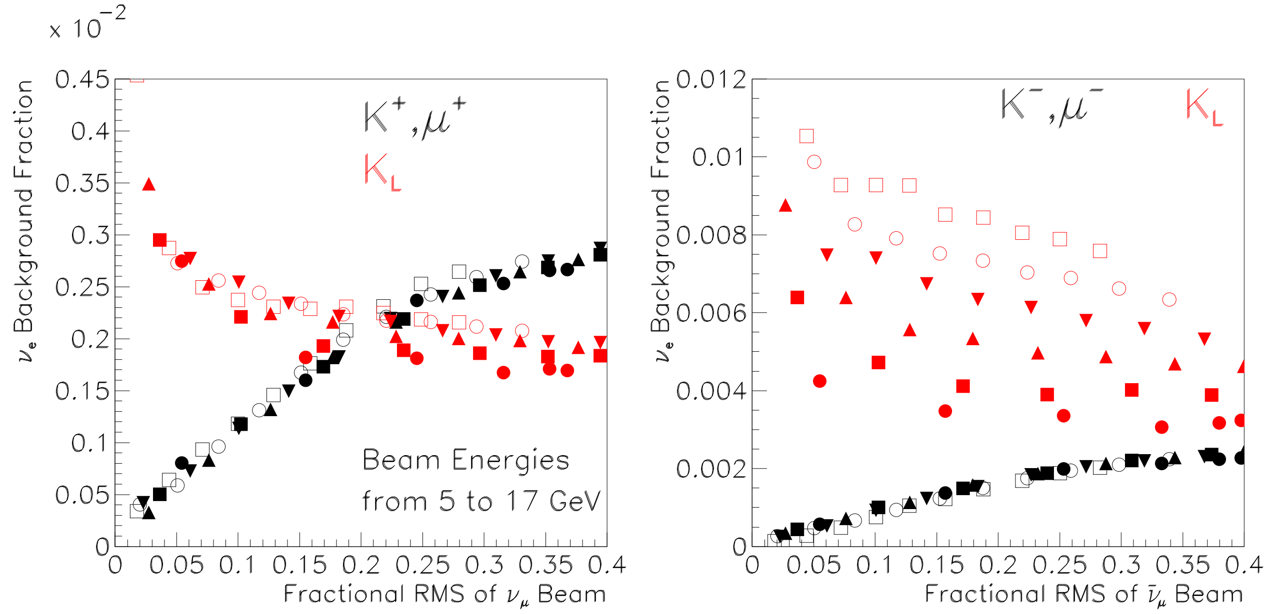


ν_τ Charged Current Events
Important for $E_\nu > 7GeV$

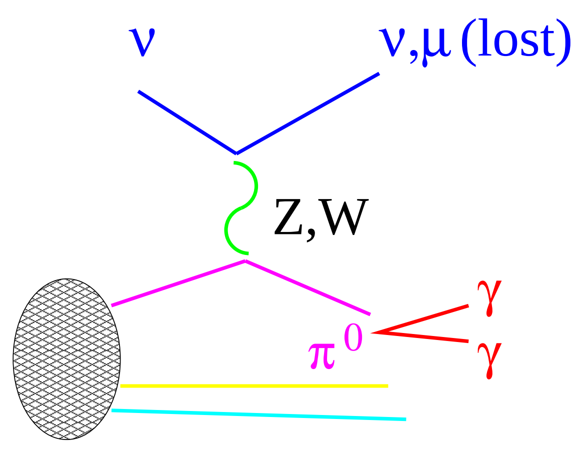
Intrinsic ν_e Background

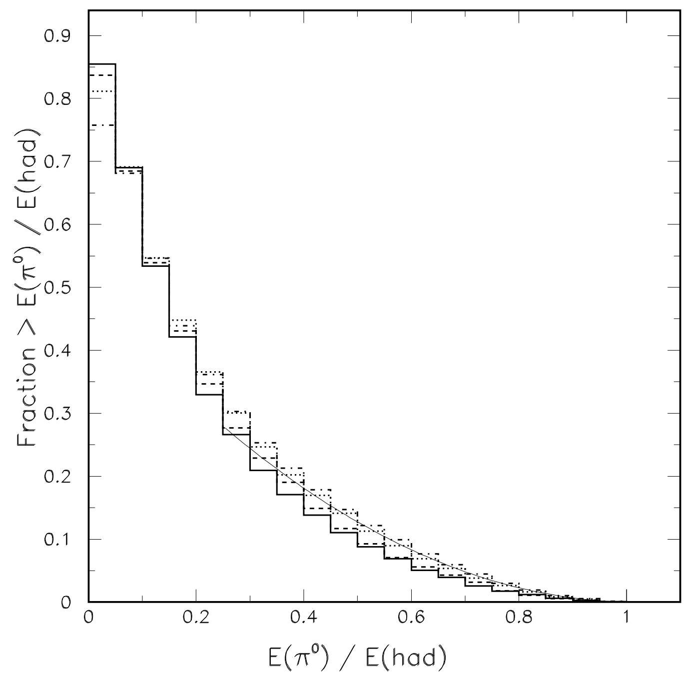


Beamline	Peak ν_μ Energy (GeV)	ν_e/ν_μ event ratio	p Energy GeV
K2K	1.4	0.7%	12
MINOS LE	3.5	1.2%	120
MINOS ME	7	0.9%	120
MINOS HE	15	0.6%	120
CNGS	17	0.8%	400
JHF wide	1	0.7%	50
JHF HE	5	0.9%	50
MiniBoone	0.5	0.2%	8
ORLaND	0.0528	0.05?%	1.3

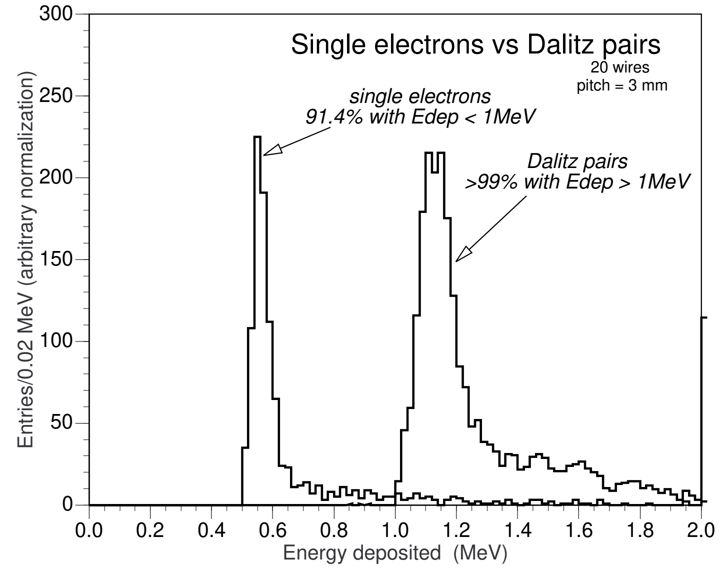


Neutral Current Background





- Liquid Argon TPC (ICARUS) (1/1000)



- fine-grained steel-drift tubes (THESEUS) longitudinal shower development (1/40)
- Water Cerenkov (K2K) (10^{-2} below 1GeV)

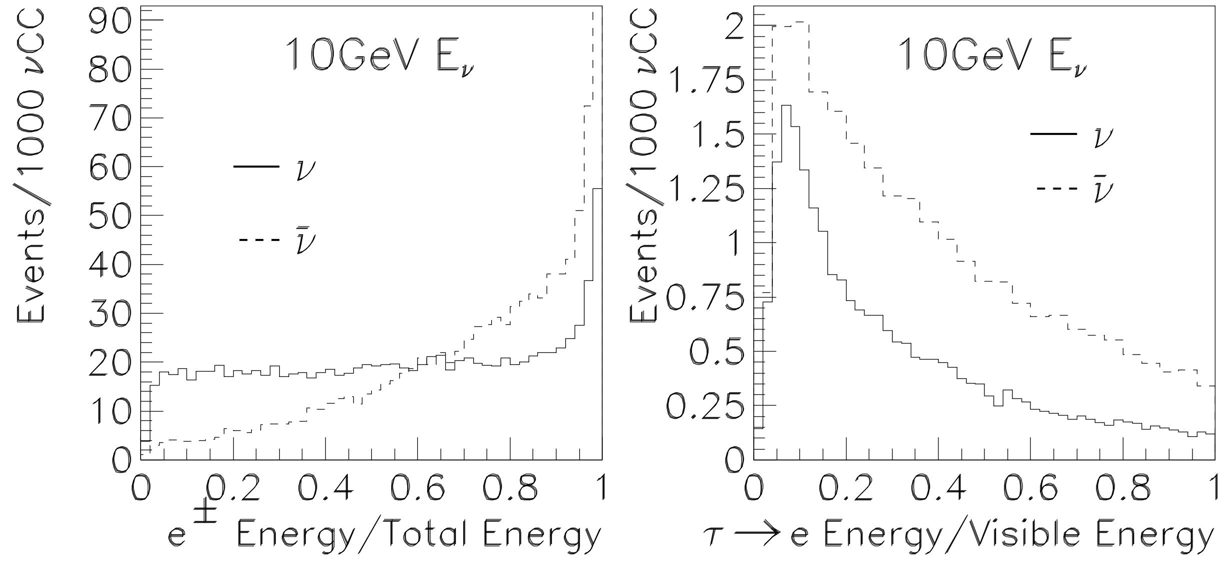
$$\nu_\mu \to \nu_\tau, \tau \to e$$

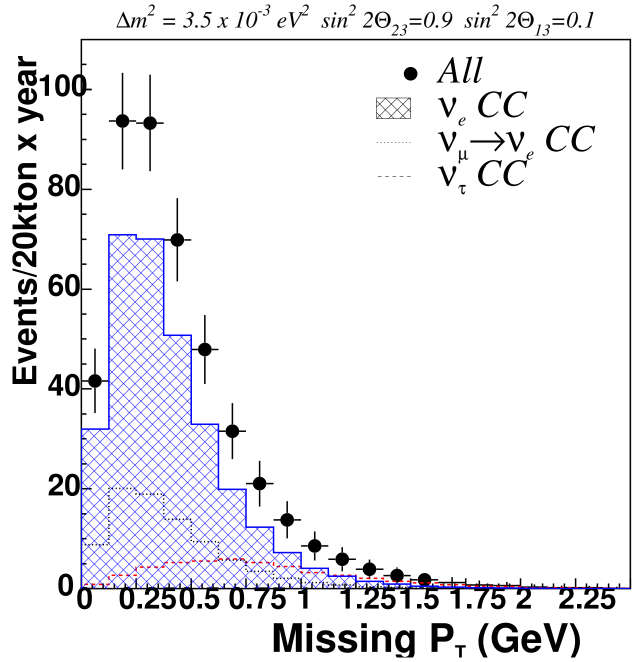
Today's discovery is tomorrow's background...

$BR(\tau \to e(\gamma)\nu_\tau\bar{\nu}_e) = 0.20$, $BR(\tau \to n\pi^0 X\nu_\tau) = 0.37$,

ν_τ flux is $\propto \sin^2 2\theta_{23} \sin^2(\delta m_{23} L/E)$ i.e. $\mathcal{O}(1)$...

Kinematic Handle on $\tau \to e$: electron energy





Other Kinematic Handles: p_T

ICANOE proposal

$\delta m^2_{23} = 3.5 \times 10{-}3$

$\sin^2 2\theta_{13} = 0.1$

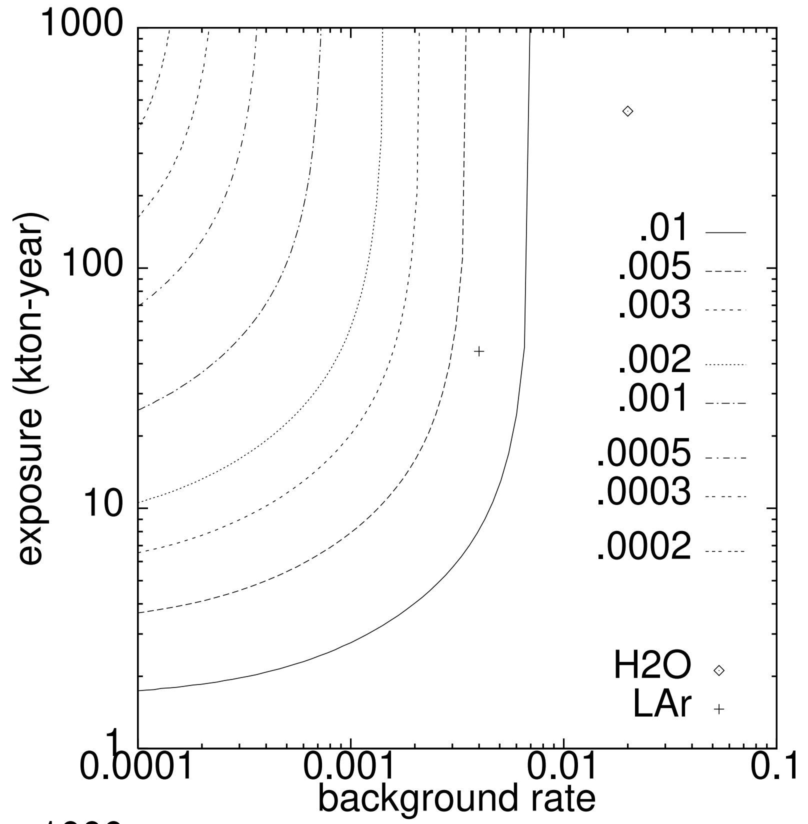
Backgrounds in Conventional Beams
Executive Summary

	Dependence on			
Background	Baseline	Detector	Beamline	Rate
NC/CC π^0 production	$1/L^2$	a lot	some	$10^{-1} \to 10^{-3}$
$\nu_\mu \to \nu_\tau$ $\tau \to e$	flat	some	some	$10^{-1} \to 0$
Intrinsic ν_e	$1/L^2$	barely	all	$10^{-2} \to 10^{-3}$

Two Regimes:

1. 1GeV beam (JHF Study)
   - ν_e, NC only
   - Could use water Cerenkov or Liquid Argon TPC
2. Multi-GeV beams (3-15GeV)
   - ν_e, NC, and maybe τ
   - Liquid Argon TPC or fine-grained steel

Measuring of $\nu_\mu \to \nu_e$ at 3σ

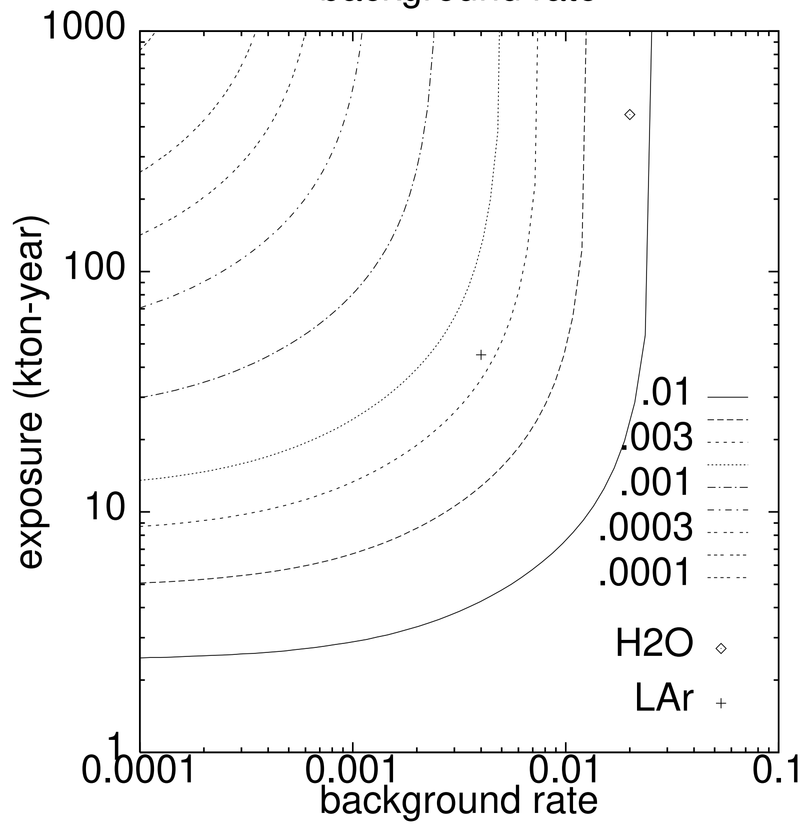


3.5GeV beam (NUMI LE) Baseline 732km

syst. error: 0.1

1.6MW Source

$\delta m^2_{23} = 3.5 \times 10^{-3}$



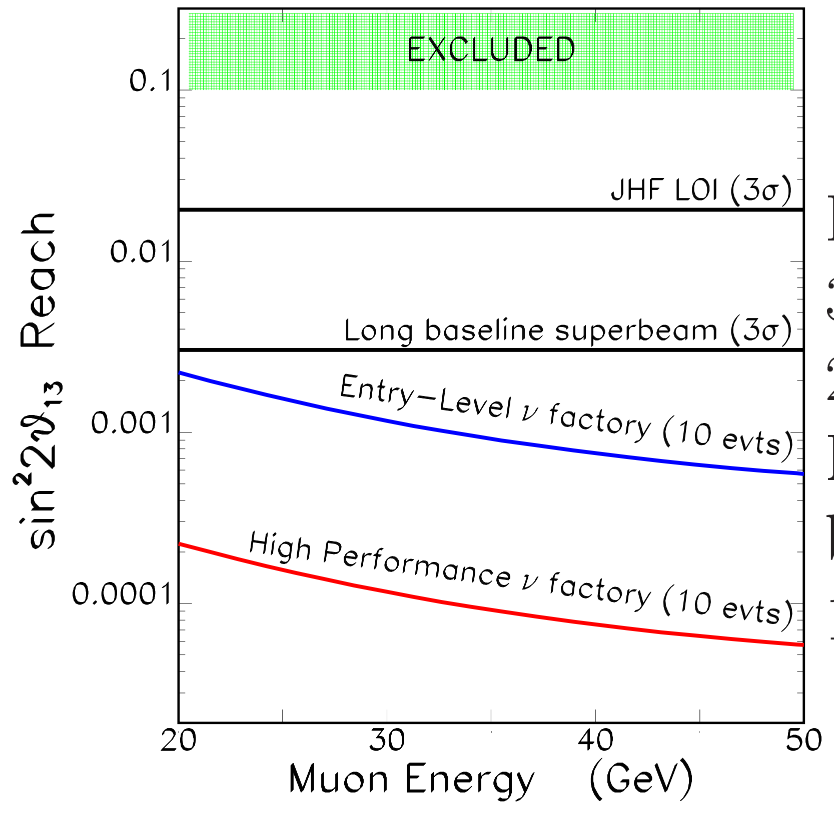
MADPH-00-1199

Barger *et al*

7GeV beam (NUMI ME) Baseline 2800km –see matter effects!

syst. error: 0.1

Upgraded Conventional Beam ($\geq 1GeV$) Conclusions



Best Bet:
30kton-yr LAr,
2800km,
NUMI-ME
beam
1.6MW Source

- Beam backgrounds are never at 1 event level
- Detector technology has a **huge impact** on backgrounds
- If $\sin^2 2\theta_{13} < 0.01$, $\nu_\mu \to \nu_e$ will be hard!
- Unambiguous CP violation only in small region of parameter space
- unambiguous sign of δm^2_{23} in limited scenarios

Snowmass Cry: We are in the middle of a fundamental discovery!

Oscillations can:

- Give insight into the theory of flavor
- Tell us about the origin of fermion masses
- suggest a high mass scale of new physics
- contribute to understanding the origin of baryon asymmetry in the universe

To understand mass and mixing...

- New Facilities
  - Upgraded proton source (1-4MW)
  - Very intense ν beams
  - Ultimately, a ν factory
- New Detectors
  - Focus on ν_e appearance
  - If LSND is oscillations: ν_τ appearance

The Case for a High Energy Superbeam

- $\nu_\mu \to \nu_e$ is extremely important for determining the mixing matrix structure
  - at any one baseline the error will be due to a combination of syst. and stat. errors on background levels
  - Two baselines and energies will ensure that oscillations are occurring and not something completely different
- The mass hierarchy may be different from what people naively expect!
  - if so the matter effects will enhance the $\sigma(\bar{\nu})$ not $\sigma(\nu)$
  - You would want the longer baseline to see it for the first time
- If JHF-HyperK sees CP violation, there would still be a 8° ambiguity due to matter effects

E1 Working Group Position Paper

- The recent evidence for neutrino oscillations is a profound discovery. The US should strengthen its lepton flavor research program by expediting construction of a high-intensity conventional neutrino beam ("superbeam") fed bya 1-4MW proton source.
- A superbeam will probe the neutrino mixing angles and mass hierarchy, and may discover leptonic CP violation. The full program will require neutrino beams at a number of energies, and massive detectors at a number of baselines. These facilities will also support a rich program of other important physics, including proton decay, particle astrophysics, and charged lepton CP and flavor-violating physics.
- The ultimate laboratory for neurino oscillation measurements is a neutrino factory, for which the superbeam facility serves as a strong foundation. The development of the additional needed technology for neutrino factories and muon colliders requires an ongoing vigorous R& D effort in which the US should be a leading partner.

Superbeam Ideas

Beamline	Baseline (km)	Detector	Authors
NUMI off axis	500,732	steel/scint	A.Para, M.Szleper
NUMI to Lake Superior	500	$H_2$0 Čerenkov	Wai, Petyt, Habig
BNL to Cornell	300	LAR TPC	S.Kahn, K.McDonald
FNAL → WIPP		LAR TPC	D.Cline, J.Learned
FNAL → NUSL		$H_2$0 Čerenkov	
BNL → NUSL		$H_2$0 Čerenkov	

Outstanding Issues:

- For LAR: getting a large enough cryogenic volume underground
- For LAR: What is the largest module you could build?
- For LAR: does it work as well in data as in MC?
- For WC: How does it work at energies above 1GeV?
- For Steel/Scint: How much segmentation is needed for enough NC rejection (at 2-3GeV)?
- For all: how can we optimize cost/kton?